

AN URBAN CANOPY PARAMETERIZATION FOR MESOSCALE METEOROLOGICAL MODELS

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1. INTRODUCTION

Buildings and urban landuse significantly impact the micro- and mesoscale flow fields (e.g., Bornstein, 1987; Hosker, 1984). Since mesoscale numerical models do not have the spatial resolution to directly simulate the fluid dynamics and thermodynamics in and around urban structures, urban canopy parameterizations are sometimes used to approximate the drag, heating, radiation attenuation and enhanced turbulent kinetic energy (tke) produced by the sub-grid scale urban elements. In this paper, we review Yamada's (1982) forest canopy parameterization and present a simple modification to account for the urban canopy. In this scheme, we have subdivided the urban landuse into residential, residential with mature trees, industrial/commercial, and downtown/city center. We have incorporated the urban canopy parameterizations into the HOTMAC mesoscale code and present results for idealized cases. At the conference, we will show preliminary model output for simulations performed in the Los Angeles basin.

2. BACKGROUND

Urban infrastructure are known to alter the wind, temperature, turbulence, and radiation budget fields. The well-known urban heat island phenomenon occurs due to thermal differences between the city and the surrounding rural area. Typically strongest at night for low wind speeds, the warmer air in the city core rises, pulling air near the surface radially inwards. Oke (1987) lists seven (sometimes competing) causes, including decreased longwave radiation loss due to reduced sky factor, decreased evapotranspiration, anthropogenic heat input, and reduced heat transport, that illustrate that the urban heat island (and sometimes "cool" island) is a complex phenomenon. The review by Bornstein (1987) reports that several field studies show wind speed deficits generally exist in urban areas, while turbulence levels are generally elevated.

For typical mesoscale meteorological models with minimum grid resolution on the order of kilometers, some sort of area-averaged parameterization is needed to account for sub-grid building effects on momentum transfer, turbulent kinetic energy (tke) production, the surface energy budget, and heat input. One common approach is to modify the roughness length and surface thermal properties to account for grid cells with urban

landuse (e.g., Hjelmfelt, 1982, Schultz and Warner, 1982). Through the use of Monin-Obukhov similarity theory, the larger urban surface roughness modifies the velocity and Reynolds stress profiles near the surface and implicitly increases the bulk drag. However, Monin-Obukhov similarity is valid only above the roughness elements (in this case the buildings) so that the computed velocity and turbulence profiles are valid above, not within, the canopy. In addition, the traditional roughness approach cannot account for local wind speed or turbulence intensity minima or maxima within the canopy (as found in the forest canopy where the wind speed is maximum at trunk level below the dense foliage region (e.g., Watanabe and Kondo, 1990) and the turbulence intensity is largest just below crown height (e.g., Cionco, 1972)). Moreover, mesoscale models do not typically account for attenuation of short- and longwave radiation due to buildings.

Below we will present the forest canopy parameterizations derived by Yamada (1982) and our modified urban canopy parameterizations. These parameterizations are not as complex as the relatively sophisticated urban canyon energy budget models (e.g., Arnfield, 1982), nor can they simulate the complicated building-scale flow features produced by computational fluid dynamics models; however, in a simple manner they do account for many of the urban canopy impacts and, in an area-averaged sense, they produce qualitatively similar results to field measurements. First, we will briefly describe the mesoscale model into which the canopy parameterizations have been incorporated.

3. MODEL DESCRIPTION

HOTMAC is a three-dimensional time-dependent mesoscale meteorological model utilizing a $1\frac{1}{2}$ order turbulence closure scheme (Yamada and Bunker, 1989). Using the hydrostatic approximation, a gradient-diffusion closure scheme for the horizontal turbulence components, and a terrain-following coordinate system, the model numerically solves the governing conservation equations for mass, momentum, heat, and moisture using the alternating direction implicit finite difference scheme. HOTMAC also includes solar and terrestrial radiation effects, the lower boundary conditions are defined by a surface energy balance and similarity theory, and the soil heat flux is obtained by solving a 5-level heat conduction equation in the soil which ignores lateral heat transfer. Surface properties are defined for sixteen landuse classes. The model has been used to simulate time-varying flows in complex terrain, including mountainous topography, coastal regions, and urban areas.

4. CANOPY PARAMETERIZATIONS

Forest Canopy. Yamada (1982) derived forest canopy parameterizations that account for momentum loss, turbulence production, and radiation attenuation. For momentum loss, a forcing term was added to the horizontal components of the standard atmospheric boundary-layer Reynolds-averaged momentum equations (e.g., Arya, 1988) to account for form (pressure) and viscous (friction) drag due to trees

$$\frac{D\bar{U}}{Dt} = f(\bar{V} - \bar{V}_g) - \frac{\partial}{\partial z} \overline{uw} + \dots - f_{tree} C_d a(z) \bar{U} |\bar{U}| \quad (1)$$

$$\frac{D\bar{V}}{Dt} = -f(\bar{U} - \bar{U}_g) - \frac{\partial}{\partial z} \overline{vw} + \dots - f_{tree} C_d a(z) \bar{V} |\bar{V}| \quad (2)$$

where f_{tree} is the fraction of the grid cell covered by trees, C_d is the drag coefficient of trees, $a(z)$ is the plant area density (plant surface area per unit volume), and the absolute value sign ensures that the drag force term is opposite the wind direction. This formulation is similar to that proposed by Wilson and Shaw (1977) and Liu et al. (1996), for example.

Yamada (1982) added similar terms to the turbulence energy (tke) and length scale (l) equations in order to account for turbulence wake generation by the trees

$$\frac{D\overline{tke}}{Dt} = \dots f_{tree} C_d \cdot a(z) \cdot (|\bar{U}|^3 + |\bar{V}|^3) \quad (3)$$

$$\frac{D\overline{tke} l}{Dt} = \dots f_{tree} C_d \cdot a(z) \cdot l \cdot (|\bar{U}|^3 + |\bar{V}|^3) \quad (4)$$

Similar eqns. were derived by Wilson (1985), though for the eddy dissipation rather than the length scale. Liu et al. (1996) proposed adding a sink term to eqns. (3) and (4) to account for the accelerated cascade of tke to small scales due to small-size leaf foliage.

The heat eqn. was modified to account for in-canopy radiative flux divergence

$$\frac{D\bar{\Theta}_v}{Dt} = -\frac{\partial}{\partial z} \overline{w\theta_v} + \dots + \frac{1 - f_{tree}}{\rho C_p} \frac{\partial R_N}{\partial z} + \left(1 + \frac{1}{B}\right)^{-1} \frac{f_{tree}}{\rho C_p} \frac{\partial R_{N_c}}{\partial z} \quad (5)$$

where B is the Bowen ratio (sensible to latent heat flux ratio) of the canopy and R_{N_c} is the in-canopy net radiation term parameterized as

$$R_{N_c} = R_{N_h} \exp\{-kL(z)\} \quad (6)$$

R_{N_h} is the net radiation at canopy top, k is an extinction coefficient, and $L(z)$ is the cumulative leaf area index defined by

$$L(z) = \int_z^{h_c} a(z') dz' \quad (7)$$

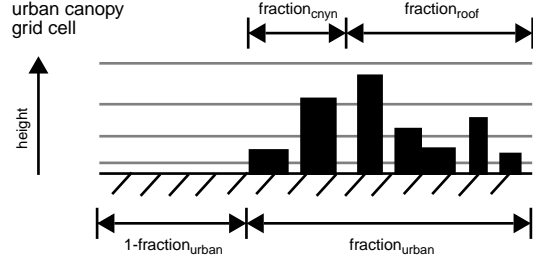


Figure 1. Illustration of how each urban grid cell is divided up into urban and non-urban fractions. The urban fraction is further subdivided into roof and canyon fractions.

where $a(z)$ is the plant area density and h_c is the height of the canopy. R_{N_h} is computed from net longwave and net shortwave at the canopy top and requires a tree emissivity and albedo to be prescribed. Note that we have not added a term to make R_{N_c} (eqn. 6) vanish at the surface when the canopy is completely covered by trees ($f_{tree} = 1$) as in Yamada (1982).

Finally, the surface energy balance eqn. is modified to include a canopy and non-canopy fractions, i.e.,

$$R_{N_g} = f_{tree} R_{N_h} \exp\{-kL(0)\} + (1 - f_{tree}) \{(1 - \alpha_G) S_G + \Delta R_{L_G}\} = H_G + LE_G + G_s \quad (8)$$

where S , ΔR_L , H , LE , and G_s are the solar, net longwave, sensible, latent, and ground soil energy fluxes, respectively and G signifies the measurements are at the ground. The forest canopy scheme requires user-specification of the canopy drag coefficient C_D , the plant area density $a(z)$, the grid cell tree fraction coverage f_{tree} , the extinction coefficient K , the canopy top emissivity and albedo, and the canopy Bowen ratio.

Urban Canopy. For the urban canopy we use the same eqns. (1) - (4), but replace f_{tree} with f_{urban} , the fraction of grid cell covered by urban structures, and use drag coefficients and canopy surface area density $a(z)$ appropriate to urban areas.

How to treat the heat and surface energy budget eqns. (5) and (8) is more complicated. A key point in our approach is illustrated in Fig. 1: we divide the urban grid cell into an urban fraction (f_{urban}) and non-urban fraction ($1 - f_{urban}$), and then further subdivide the urban canopy fraction into roof fraction (f_{roof}) and “between-building” fraction (f_{cny}). Then, eqn (5) is modified to include anthropogenic and rooftop heat sources and a flux divergence term between the buildings

$$\frac{D\bar{\Theta}_v}{Dt} = \dots + \frac{1 - f_{urb}}{\rho C_p} \frac{\partial R_N}{\partial z} + \frac{f_{urb} q_{urb}}{\rho C_p \Delta z} + \left(1 + \frac{1}{B}\right)^{-1} \left(\frac{f_{urb}}{\rho C_p} \frac{\partial R_{N_c}}{\partial z} + \frac{f_{roof} q_{roof}}{\rho C_p \Delta z} \right) \quad (9)$$

where the anthropogenic heat flux q_{urb} is user-specified, the in-canopy between-building net radiation R_{N_c} is

computed according to the attenuation eqn. (6), and the roof top heat flux is calculated from

$$q_{\text{roof}} = R_{N_h} - R_{L_{\text{roof}}} = (1 - \alpha_{\text{roof}})S + \Delta R_{L_h} - \epsilon_r \sigma T_r^4 \quad (10)$$

Here we assume that the rooftop is infinitely thin and all solar radiation absorbed by the roof is immediately re-emitted as longwave and sensible heat, i.e., the roof has no storage capacity. Currently, however, we assume that the building rooftops longwave radiate at air temperature. In addition, we have not accounted for heating by the building walls, although their extra surface area may be important (Voogt and Oke, 1997).

Rather than add the anthropogenic and rooftop heating terms to the surface energy budget (eqn. 8), we assume that the heat is released directly into the air. The surface energy budget for an urban grid cell becomes

$$R_{N_G} = f_{\text{cynyn}} R_{N_h} \exp\{-kL(0)\} + (1 - f_{\text{urban}}) \{(1 - \alpha_G)S_G + \Delta R_{L_G}\} = H_G + LE_G + G_s \quad (11)$$

Canopy Parameters. A major challenge lies in determining the different coefficients that are needed for the canopy parameterizations. Data is sparse and may contain large uncertainties.

Landuse. We are using four urban landuse classes that utilize canopy parameterizations: downtown/city center, industrial/commercial, residential with mature trees, and residential w/out mature trees. The principal distinguishing characteristics between these categories are canopy height and built vs. green space fractions. Although these quantities are site-dependent, Table 1 provides typical ranges found in the literature.

Table 1. Urban Landuse Properties

	downtown/ city center	industrial/ commercial	residential
f_{urban}	0.8-1.0	0.9-1.0	0.5-0.7
f_{roof}	0.3-0.4	0.3-0.4	0.15-0.25
f_{cynyn}	est. 0.5-0.6	est. 0.6-0.7	0.15-0.4
h_c [m]	15-100's	5-25	5-15
Bowen ratio	1.5- ∞	1.5- ∞	0.5-1.0
urban albedo	0.1-0.27 (avg. 0.15)		
urban emissivity	0.85-0.96 (avg. 0.95)		
roof albedo	0.08-0.35		
roof emissivity	0.90-0.92		

sources: Byun and Arya (1990), Grimmond and Oke (1995), Oke (1987), Theurer (1996), Voogt and Oke (1997), Wilmers (1991).

Surface Properties. The Bowen ratio is especially problematic as its value depends on weather and city watering policy, but we generally expect larger values for greater built-up fractions. Urban and rooftop albedo and emissivity measurements cover a wide range of values

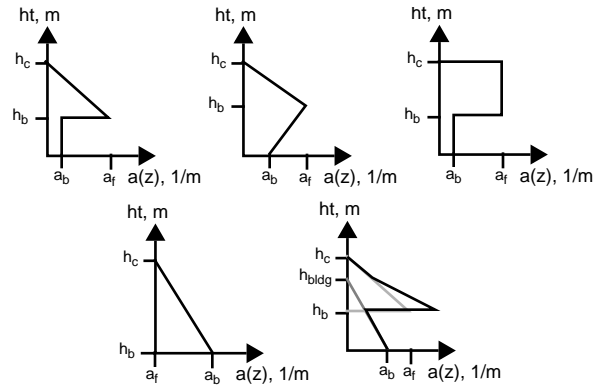


Figure 2. "Shape profiles" used for describing the canopy surface area density $a(z)$ [m^2/m^3]. Four parameters are needed for describing the profiles: canopy height, base height, base surface area density, and foliage surface area density.

as well and generally have not been broken down by urban landuse type. Currently we are using a constant extinction coefficient k , but we feel it should be made a function of solar azimuth angle and sky view factor.

Molecular Properties. We have used $\rho = 2300 \text{ kg/m}^3$, $C_p = 880 \text{ J/(kgK)}$, and $k = 1.2 \times 10^{-6} \text{ m}^2/\text{s}$ for all urban landuse types in the surface energy budget balance. When converted to thermal admittance ($\rho C_p k^{1/2}$), our values fall within the 800-3000 range given by Oke (1987).

Drag Coefficient. Hoerner (1965) lists C_D values ranging from 0.7 to 1.5 for different size and shape buildings. Although there should be dependence on number, spacing, height, and shape of buildings, as well as approach flow angle, we use an average value of 1.0 for all urban landuse categories. For trees, we are using the value of $C_D = 0.2$ given by Yamada (1982). Irvine et al. (1997) and Shaw and Schumann (1992) deduced values of 0.20 and 0.15, respectively, for forested areas.

Canopy Area Density. There are numerous measurements of $a(z)$ for different vegetative canopies (e.g., Arya, 1988; Watanabe and Kondo, 1990), but we have not found $a(z)$ profiles in the literature for the urban canopy. However, in earlier studies we have hypothesized a pyramid-shaped canopy area density profile for a mixed distribution of buildings (Brown and Williams, 1997). The shape functions we are using for forest and urban canopies are shown in Fig. 2. They are analytical functions so that the cumulative canopy (leaf) area index (eqn. 7) can be easily computed. We use a mix of the pyramid and fir tree shapes for residential areas with mature trees which several authors have indicated may in fact be better described by a forest canopy (e.g., Oke, 1989).

5. Idealized Test Case Results

We have run simulations with the HOTMAC model over flat terrain with 18 km square patches of forest and urban canopy in the center of the domain. Fig. 3 shows vertical profiles of wind speed, tke , and potential temperature upstream and in the urban canopy patch. Using shape fn. 4 for the urban canopy, a large retardation of wind, elevated levels of tke , and a "well-mixed" tempera-

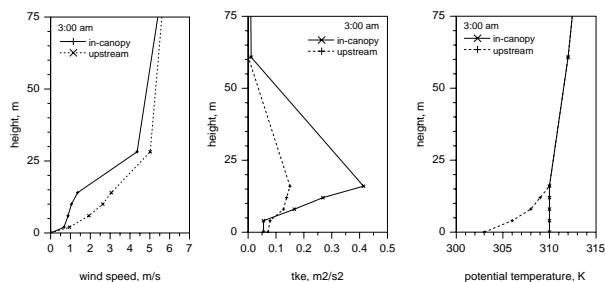


Figure 3. Model-computed vertical profiles of wind speed, tke, and potential temperature at non-urban (upstream) and urban (in-canopy) sites. Canopy height = 22 m.

ture profile are seen within the canopy. For the forest canopy (not shown here) a slight wind speed maximum was found at trunk level. Results for other meteorological variables can be found in Brown and Williams (1997).

6. Conclusions

Urban canopy parameterizations have been developed for use in mesoscale models by performing a simple modification of Yamada's (1992) forest canopy parameterization scheme. The modified scheme appears to give qualitatively reasonable answers, thus allowing mesoscale modelers to better account for the influence of urban areas. More validation needs to be done with hard-to-find area-averaged urban meteorology measurements. The uncertainties in the input parameters needs to be better quantified as well.

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Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: **An Urban Canopy Parameterization
for Mesoscale Meteorological Models**

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SUBMITTED TO: **AMS 2nd Urban Environment Conf., Albuquerque, NM
Nov. 1998**

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